COMMUNICATION PROPERTIES OF SELF-ORGANIZING NETWORKS (SWARMS) AS INFERRED FROM OPTICAL MECHANICS

B. Lemasson[*] and J. J. Anderson
School of Aquatic & Fishery Sciences, University of Washington
Seattle, Washington 98195

R. A. Goodwin
Environmental Laboratory, U.S. Army Engineer R&D Center
Portland, Oregon 97208

ABSTRACT

A primary question in our research is to determine how much sensory processing is necessary to maintain a network's resiliency to fission, or collapse, while minimizing the degree of disorder in communication. Biological components capable of governing these processes include perception, thresholds, and simple decision filters. We present a self-propelled particle model (s.p.p.) with simplified optical rules in which individual interactions are dictated by retinal representations of object bearing and motion. Optical signals are weighted by individual perception and the degree of redundant neurological stimulation. In turn, signals that exceed a threshold value serve to identify influential neighbors within the swarm's global network. Individual connections (i.e., each influential neighbor) is normalized to the individual's immediate surroundings, making the decision process adaptive to both physical and behavioral variability.

1. INTRODUCTION

Biology abounds with examples of complex sensory and motor control systems that continue to exceed the most advanced artificial systems (Higgins, 2001). This individual level of complexity is exceeded perhaps only by the degree of coordination demonstrated by collective animal behavior. Effective communication in animal groups has spurred research into artificially influencing collective decision-making in animals (Halloy et al. 2007), solving engineering problems (Casanova and Deneubourg, 1999; Gaing, 2003), and assisting with crowd safety management (Helbing et al. 2000). Yet, despite these advances, we have only a rudimentary understanding of the sensory processes linking rapid individual decision making with collective behavior, even within such model systems as krill swarms or fish schools (Warburton, 1997; Couzin et al., 2006).

Flocks of birds and schools of fish display a mesmerizing degree of synchronization in their collective motion. Such rapid decision-making by the individuals is based on neighbor movement patterns, which, although surely involving multiple sensory processes, has been repeatedly linked to vision (Warburton, 1997). One reason for this assumption is the speed with which visual information can be processed, ranging from 120 ms (humans, Kirchner and Thorpe, 2006) down to 40 ms (fish, Schlegel and Schuster 2008; flies, Wagner, 1986).

Neural architectures vary across taxa, which can profoundly impact visually mediated behaviors (Srinivasan and Zhang, 2004). Despite variability in the neural substrates, the computational principles responsible for encoding motion are similar from flies to humans (Borst and Egelhaaf, 1989). Recent efforts have demonstrated that both object identification and rapid decision-making based on motion information can be accomplished with only the neural processing available at the retinal level (Schlegel and Schuster 2008, Ölveczky et al. 2003).

In the present study, we define individual perception based on how neural information of motion is processed at the retinal level. We begin by presenting a standard model for collective behavior and then proceed to compare the model's dynamics using its behavioral rules *vs.* our optical rules.

2. MODEL

2.1 Standard Model

Self-propelled particle models (s.p.p.) of collective behavior vary in complexity, yet most involve velocity matching among individuals, complemented with attraction and repulsion tendencies (Aoki, 1982; Vicsek et al. 1995; Gregoire et al. 2003). In this framework, N individuals are represented as spheres on an infinite surface that update their positions (C_i) in discrete time steps (Δt). Directional decisions represent the sum of an individual's current motion (V_i) and the social influence of it neighbors (S_i):

$$C_i(t + \Delta t) = C_i(t) + \left[V_i(t) + S_i(t) \right] \qquad (1)$$

where an individual's social vector, S_i, is a function of

Report Documentation Page

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
DEC 2008	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Communication Properties Of Self-Organizing Networks (SWARMS) As Inferred From Optical Mechanics	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
School of Aquatic & Fishery Sciences, University of Washington Seattle, Washington 98195	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002187. Proceedings of the Army Science Conference (26th) Held in Orlando, Florida on 1-4 December 2008, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**10**	

speed, $\rho_j(t)$, and direction, $\theta_i(t)$. Socially influenced behavioral decisions are based on a subset of N influential neighbors, each conveying a signal relating either their relative position (bearing, unit vector, $\vec{B}_{i,j}$) and/or their heading (velocity, unit vector $\vec{V}_j$). Given this information, an individual avoids collisions by turning away from the set of neighbors (N^R) that intrude on some prescribed range of personal space:

$$\theta^-(t) = -\sum_{j\neq i}^{N^r} \left[\omega_{i,j}(t)\cdot\vec{B}_{i,j}(t)\right] \qquad (2)$$

While not avoiding collisions, individuals respond positively to detectable neighbors by turning towards them and/or matching their headings:

$$\theta_i^+(t) = \sum_{j\neq i}^{N^\lambda} \lambda_{i,j}(t)\cdot\vec{V}_j(t) + \sum_{j\neq i}^{N^\omega} \omega_{i,j}(t)\cdot\vec{B}_{i,j}(t) + \eta\cdot\vec{\varepsilon}(t) \quad (3)$$

where the relative strength of the geometrical signals, $\vec{V}_j$ and $\vec{B}_{i,j}$, are weighted ($\lambda_{i,j}$, $\omega_{i,j}$). The terms in brackets represent the desired heading of a subject (θ_i) based on the *explicit* knowledge of a neighbor's range, bearing and heading. These geometrical signals are prone to sensory error due to environmental noise, represented as a random direction ε with strength η. Here we assume that the signals involved in collision avoidance are devoid of sensory error due to their immediate proximity to the subject.

Changing the weight of either geometrical signal *(λ, ω)* alters a group's physical structure (e.g., liquid, gas, crystal; Gregoire et al., 2003); an approach that yields general, system level understanding, but fails to elucidate *how* individuals come to demonstrate such behavior. In order to reflect a self-organizing process it is also important to limit the degree of information sharing between the group members, otherwise the members simply follow one global rule (Gregoire et al., 2003). This standard model for collective behavior therefore highlights two important questions: how do individuals vary the influence of their neighbors (λ, ω), and how do they determine which of those neighbors have pertinent information (N^ω, N^λ)?

2.2 Optical model

As an animal moves through its environment, its motion, and those of the objects around it, together generate a collage of shifting images on its retinal surface. These movement patterns within the optic flow in turn provide the information necessary for guidance navigation (Boeddeker et al., 2005). Movement information within the optic flow is not explicitly represented by the photoreceptors, but must be processed by the nervous system based on the spatio-temporal dynamics of the retinal images (Borst, 2007). Here, we incorporate spatial principles of visual motion detection within the geometrical framework of the s.p.p. model. We first discuss image formation and then proceed to categorize visual information based upon the spatial dynamics of an image's movements. We hypothesize that the symmetry in an image's motion reflects the quality of the information, which, in turn, reflects the behavior elicited by a given stimulus (i.e., repulsion, attraction, alignment). The quality of a motion signal is inversely related to the degree of redundancy in its spatial information.

2.2.1 Image formation

In our optical model individuals are treated as point sources of light, i.e., each emitting light equally in all directions. Neighbors found within a subject's field of view are projected onto its retina using the same bearing and velocity vector information as in the standard model (Eq. 3). The retina is represented as a single dimension aligned with the subject's heading. As a neighbor approaches a subject, that neighbor's projected retinal image expands at a geometrical rate (Rind and Simmons 1999), which we express:

$$\Omega_j = c/d_{i,j} \qquad (4)$$

where Ω_j is the looming angle measured in degrees of arc, c is a constant and $d_{i,j}$ is the physical distance between the subject i and neighbor j.

Image formation requires that the retinal image cover a threshold number of cells (Lythgoe, 1979) and so we define neighbors as being visible once their projected image exceeds a minimum size: $\Omega_j \geq \Omega_{Min}$. Visible images are then sorted from largest (i.e., nearest) to smallest (farthest). For practicality, image occlusion begins once $\sum_{j\neq i}\Omega_j > ARC°$, where *ARC* is the individual's angular field of view extending to either side of a subject's heading, $\vec{V}_i$.

Repulsion supersedes attraction and alignment and is triggered when an image exceeds a maximum angular size, $\Omega_j > \Omega_{Max}$, at which point the subject is repelled by that image ($j \in N^R$; Eq. 2). Visible images below the repulsive threshold are then weighted according to their size and the symmetry of their retinal movement.

2.2.2 Motion signals

Motion within the optic flow has two components: symmetrical expanding/contracting motion (e.g., looming stimuli) and asymmetrical motion (e.g., translational flow; Collett, 2002). Symmetrical information is produced by

the component of motion along the bearing to an object. As a retinal image expands symmetrically it simultaneously stimulates an increasing number of light sensitive cells found within a ganglion's receptive field. Yet, despite the increase in neural activity, the information across the image field is redundant, so that the amount of novel, or pertinent, information concerning an object's bearing, $\vec{B}_{i,j}$, does not increase.

To address this problem of signal redundancy, Tsukamoto et al. (1990) concluded that information within a ganglion's receptive field is encoded by comparing the degree of spatial correlation within the center of a ganglion's receptive field to that found in the surrounding area. Differences between the spatial correlations found within these region serves to amplify the novel components of the spatial information and reduce the influence of redundant information.

Based on the above reasoning we hypothesize the following series of relationships. A newly visible image (Ω_j) will stimulate only a restricted region within the center of a ganglion's receptive field, at which point the degree of spatial correlation across the entire field will be closest to its lowest value. As the image expands symmetrically across the field, the degree of spatial correlation within the field increases asymptotically until the image covers the entire receptive field and all spatial signals are equivalent. The difference in the spatial correlations between the originally stimulated field center and the surround decays as the image spreads, in which case the quality of the symmetrical signal can be expressed as:

$$\omega_j = \frac{1}{\sqrt{\Omega_j}} \qquad (5)$$

Substituting Eq (4) into Eq. (5) translates a symmetrical signal's quality in terms of the object's actual range from the subject:

$$\omega_j = \sqrt{d_{i,j}} \qquad (6)$$

Asymmetrical movement of a retinal image causes a turnover in spatial information without any increase in redundant spatial information. The sensitivity of a ganglion to asymmetrical stimulation is based on the number of new cells stimulated per sampling period, which is a function of the speed of the retinal image's edge. As an object's perceived speed decays with distance, the quality of the information is a function of the object's actual speed ρ and its range:

$$\lambda_j = \rho_j / d_{i,j} \qquad (7)$$

Although an object's range scales its apparent motion, the relative strength of either motion signals also depends on the subject's perspective (Collett, 2002).

Perspective is the angular difference in the subject's heading and the signal's bearing:

$$\alpha_{i,j} = \measuredangle\left(\vec{V}_i, \vec{B}_{i,j}\right) \qquad (8)$$

Symmetrical stimuli peak in their relative influence with motion along the line of sight ($\alpha_{i,j} = 0°$) and decay as the cosine of $\alpha_{i,j}$. In opposition to this, translational stimuli peaks in strength when $\alpha_{i,j} = 90°$ and decay as the sine of the angle (Collett, 2002). Thus, adjusting for the angular dependence of image perception, Eq. (6) and Eq. (7) become:

$$\omega_j = \cos(\alpha_{i,j})\sqrt{d_{i,j}} \qquad (9)$$

$$\lambda_j = \sin(\alpha_{i,j})\rho_j / d_{i,j} \qquad (10)$$

The above process is repeated for all visible stimuli within each subject's optic flow and dictates signal quality.

2.2.3 Signal detection

Weber's law states that an organism will respond to a just noticeable difference in signal intensity relative to a background level of stimulation (Rapoport, 1983). Here we adopt a modified version of this relationship by normalizing the magnitude of each signal, ω_j and λ_j, by the instantaneous background level of stimulation defined as the mean value across all pooled retinal images. Those normalized signals that exceed detection thresholds (k^λ, k^ω) 'pop-out' from the background to convey bearing and/or heading information, thereby identifying the set of influential neighbors (N^λ, N^ω). Otherwise, signals that fall below their designated threshold are ignored.

To summarize, the geometrical properties of a neighbor's behavior ($\vec{V}_j, \vec{B}_{i,j}$) are expressed by the motion of it's retinal projection; a perception that is scaled by the distance and angle of the object. The number of images that can be processed is first limited by occlusion and then by comparing their normalized values to a threshold. Signals that do not elicit a repulsive maneuver (Eq. 2) and exceed the background threshold, will influence a subject's motion (Eq. 3). The process is repeated across the population and all individual positions are updated synchronously using Eq. (1).

2.3 Analysis

We first determined how varying the sensory thresholds impacted the degree of order, cohesion, and connectivity within the optical model. Order represents the degree of angular equivalence across all headings, cohesion was measured as the average nearest neighbor

distance (*NND*), and connectivity reflects the average number of influential neighbors within a randomly selected subject's interaction network over time (Π). We then tested the ability of individuals to adapt to behavioral anomalies from members outside their immediate network of influential neighbors. Finally, we explored the effect of neighbor influence and the degree of connectivity on the group's communication resilience in the face of increasing environmental noise (e.g., turbulence).

3. RESULTS

3.1 Model Dynamics

Under behaviorally homogenous conditions (i.e., constant speed) the optical model retained several of the physical phases expressed by the standard model. Groups displayed a sharp transition between states of fusion and fission (Fig. 1a) and cohesive groups varied between ordered/disordered formations (Fig. 1b). Cohesive, highly ordered motion generally relied on individual's taking a mean field approach to translational stimuli, which entailed a large number of influential neighbors ($k^{\omega} \geq 1.5$; $0.0 \leq k^{\lambda} \leq 0.7$; $NND: 1.3 \rightarrow 2.8$; $\phi: 0.8 \rightarrow 1.0$; $\Pi: 13.2 \rightarrow 45.8$). However, a narrow range did emerge along the base of the density tower (Fig. 1a) where increasing the asymmetrical motion threshold resulted in organized, cohesive motion based on smaller interaction networks ($k^{\omega} \geq 1.6$; $1.1 \leq k^{\lambda} \leq 1.4$; $NND: 1.7 \rightarrow 5.2$; $\phi: 0.7 \rightarrow 1.0$; $\Pi: 4.6 \rightarrow 11.6$).

The size of an individual's interaction network (Π) was positively correlated with the group's degree of sparseness (increasing NND; Spearman's $r = 0.82$, P < 0.001), which was primarily due to occlusion. Yet, although the number of occluded images was negatively correlated with group sparseness (increasing NND; Spearman's $r = -0.86$, P < 0.001) the decision filter further reduced the size of the individual's interaction network within this optically defined locality (Table 1).

Table 1. The effect of the threshold filter on group order (ϕ), cohesion (*NND*), and the number of influential neighbors (Π). All differences were significant at P < 0.001 using a wilcoxon rank–sum test. Simulation parameters: $N = 50$, $k^{\omega} = 2.0$, $k^{\lambda} = 1.1$, remaining parameter values are the same as in Fig 1.

	Filter On	Filter Off
ϕ	0.89 ± 0.18	0.19 ± 0.02
NND	1.6 ± 0.25	1.1 ± 0.0
Π	8.0 ± 2.2	15.9 ± 1.3

3.2 Network Adaptability

In the case of an attack on the group, any sudden change in a potential signaler's range to a subject would be predicated by a sudden shift in its behavior. Individuals using smaller interaction networks (Fig. 1) would have a lower probability of being directly 'connected' to that signaler. To address how well individuals could adapt to such sudden changes in their optic flow we used a fixed network test (Pimentel et al. 2008).

Fixing individual positions isolates any responses to behavioral shifts (excludes range effects) and reduces the degrees of freedom in the communication channels, i.e., repulsive and attractive signals are omitted. A small group of 25 individuals were initialized with identical headings and a receiver with a small number of interactions ($\overline{\Pi} = 5 - 6$) was positioned in the upper right hand corner of the lattice (Fig. 2). Members of the group interacted with their set of influential neighbors and exchanged only heading information. After 10 iterations, a signaler was chosen at random from outside the receiver's interaction network, yet within its detection range, and altered its behavior by turning $90°$ and increasing its speed.

Our perception rules assume that each individual has a fixed gaze and is not continually scanning their surroundings using rapid eye, or head motions. The influence of such saccades would reduce the angular component of motion perception. We therefore investigated groups whose perception of their surrounding neighbors was based either on a fixed or flexible gaze. Fixed gaze weighs signal perception using Eq. (9 & 10), while a flexible gaze weighs perception by Eq. (6 & 7).

The probability of explicitly detecting a signal from outside a subject's interaction network, yet still within detection range, increased asymptotically with signal strength and was limited by the influence of signal bearing (Fig 3). Small changes in speed showed a reduced probability of explicit detection of the signal. Such a difference is favorable, as individual speeds are expected to vary slightly within a group and moderate shifts in movement behavior within the optic flow have a greater chance of being ignored.

Additionally, detection of the signaler occurred immediately after the jump in signaler speed and was quickly lost (Fig. 2). As the signaler's immediate neighbors adapted to its change in behavior, their own responses subsequently served to mask the signal source, as the background signal level increased and the receiver's interaction network fell back down to its nominal size.
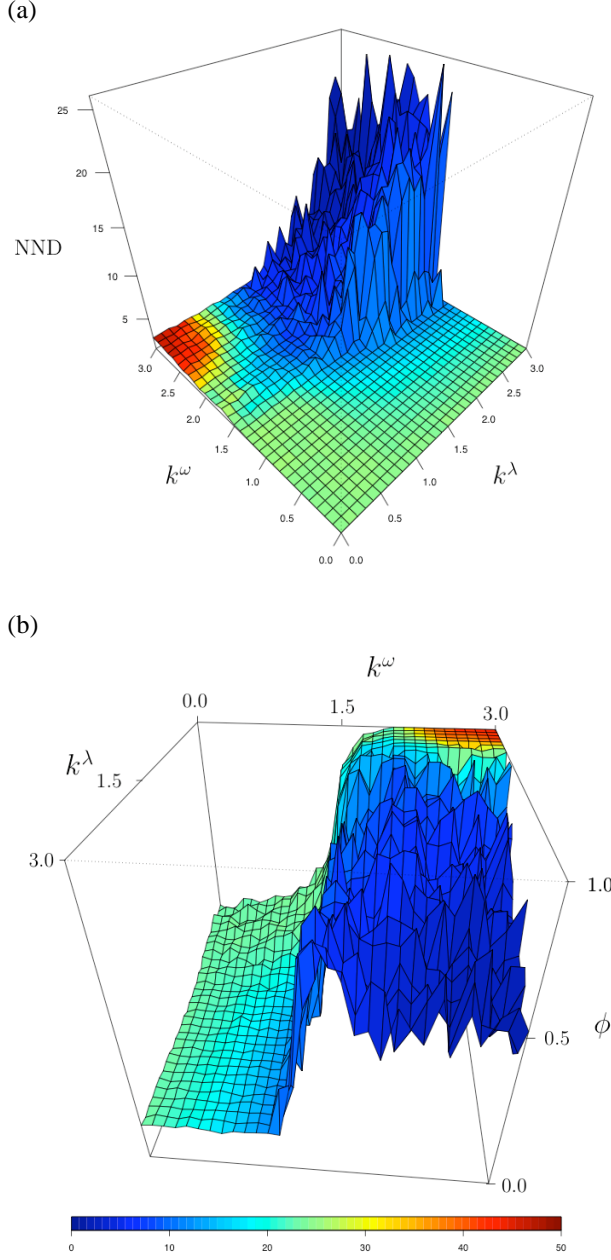
(a)

(b)

Fig. 1. Group cohesion (a; *NND*) and order (b) based on changes in symmetrical (k^ω) and asymmetrical (k^λ) threshold values. Order is the degree of dispersion in angular headings (*V*); varying from disorder ($\phi = 0$) to order ($\phi = 1$). Color represents the average size of an individual's interaction network, which varied from 1 to 45. Model parameters: $N = 50$; $\Omega_{Min} = 0.2°$, $\Omega_{Max} = 45°$; $\rho = 2\ L{\cdot}s^{-1}$, *ARC* $\pm165°$. Decisional error has a strength of $\eta = 1$, and δ is drawn randomly from a wrapped normal distribution with a standard error of $5°$. Simulations lasted 2,000 time steps and statistics were calculated using the last 500 time increments. Each node of the surface represents the mean of 10 replicates.
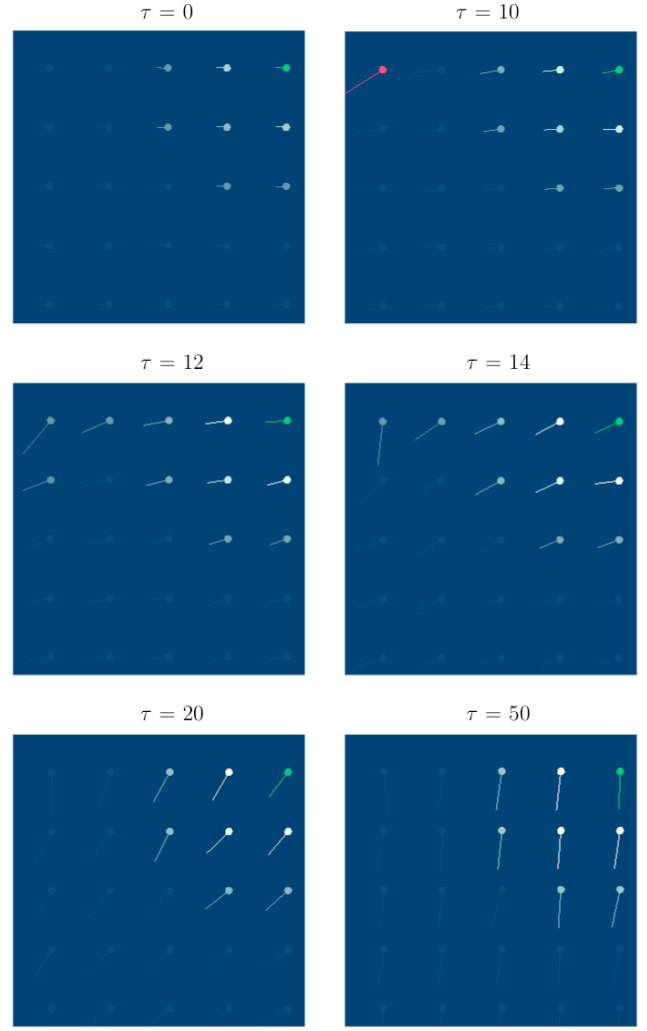

Fig 2. Network adaptability to novel stimuli. The network of influential neighbors for a 'receiver' (green) are displayed in white and decay in strength with distance from the subject until they become 'invisible' (blue) and fade into the background. Individuals begin with an agreed upon direction ($0°$). At time step $\tau = 10$ the signaler's alters its behavior (red) causing it to 'pop-out' from the background. Within a brief period of time, the once novel behavior has spread and becomes the new background level of stimulation, after which the receiver's network returns to its original size. Parameters: $k^\lambda = 1.2$, $k^\omega = 1.4$, $\Omega = 70°$, *ARC* $= \pm180°$, and angular perception is off.
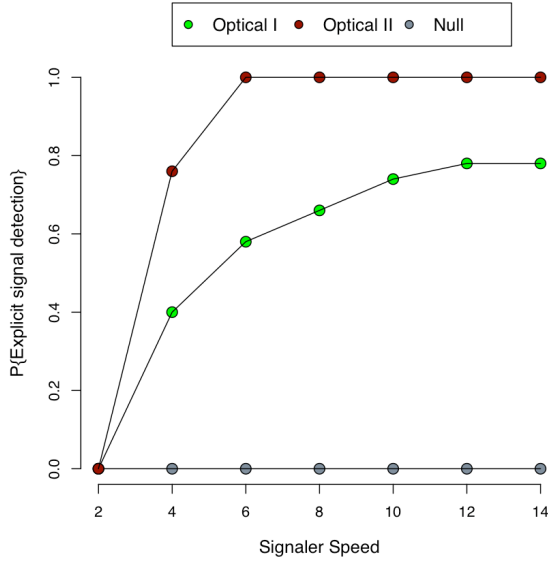
Fig. 3. Probability of detecting novel stimuli within a subject's optic flow as a function of signaler speed ($L \cdot s^{-1}$). All group members were visible to the receiver, but the receiver's interactions were predominantly limited to the 5-6 nearest neighbors (i.e., 75-80% of the group's movements are generally ignored). A fixed gaze (green points) limited maximum probability of detecting a novel stimulus, as compared to a flexible one (red points). A fixed topology would never explicitly incorporate influential members into its interaction network based on changes in their behavior (grey circles). Parameters for the optical model: $k^{\omega} = 2.1$, $k^{\lambda} = 1.2$, $\Omega_{Max} = 45°$. We conducted 50 replicates at each speed to estimate the probability that the receiver explicitly detected the signaler's behavior.

3.3 Resiliency

Using the fixed network approach, we tested the resiliency of groups with small and large interaction networks (Π). Resiliency tests how well communication within the group is maintained under increasing levels of environmentally induced error (e.g., turbulence). Specifically, we were interested in discovering if the weighting rules (i.e., $\omega_j \neq \omega_{j+1} \neq \omega_{N^{\omega}}$, $\lambda_j \neq \lambda_{j+1} \neq \lambda_{N^{\lambda}}$) reduced the resiliency of the group, as compared to a more strongly interconnected network where all signals were treated equally, which is the situation in the standard model ($\omega_j = \omega_{j+1} = \omega_{N^{\omega}}$, $\lambda_j = \lambda_{j+1} = \lambda_{N^{\lambda}}$). We used the standard model as our null model and set each individual's interaction topology based on the number of connections recorded in the optical model using both large and small Π.

Scaling neighbor influence according to our optical rules did not reduce the system's resiliency to sensory

error with respect to the null model's performance. Both the weighted (optical) and equivalent (null) interaction rules displayed high resilience to moderate levels of sensory error (Fig. 4). Each combination (model x Π) demonstrated a continuous decline in resiliency as noise levels increased, with the exception of the highly connected null model. Interestingly, the 'small-world' optical model displayed an improvement in group-level resilience over the larger interaction network; a pattern that was reversed in the null model.
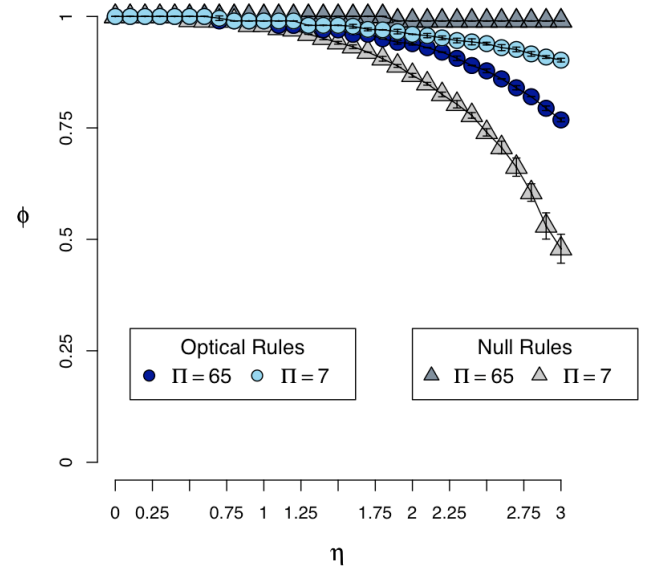

Fig 4. Collective resilience of arrayal information to increasing levels of sensory error within groups of small and large interaction networks. All points represent the mean of 10 replicates and their standard deviation; error bars are often smaller than symbol size. Parameters: Both optical models share: $N = 100$, $\rho = 2 \, L \cdot s^{-1}$, $ARC \pm 165$ with a flexible gaze. Optical models: $\Pi = 65$, $k^{\lambda} = 1.2$, $k^{\omega} = 2.1$; $\Pi = 7$, $k^{\lambda} = 0.2$, $k^{\omega} = 2.6$; remaining parameters were the same as in Fig. 4; Null model: $N^r = 1$, $N^o = 50$. All interactions occurred on a fixed lattice and only headings changed over time. Sensory error was added to each detected signal.

CONCLUSIONS

The focus of our research is to develop simple, biologically inspired algorithms to effectively incorporate neural processing concepts into the traffic rules governing collective animal motion. Groups of individuals must be able to interact efficiently and adapt to novel stimuli in their environment in order to respond collectively. Individuals using a dynamic interaction network can vary their interactions based on environmental conditions (e.g., group sparseness, turbulence) as well as neighbor behavior. Focusing on vision enables us to draw on both

biology and engineering to integrate the image patterns generated on a sensor (e.g., an electronic eye) with rapid signal processing and decision-making. Additionally, by maintaining simple geometrical assumptions (symmetrical *vs.* asymmetrical stimulation), it will be possible to perform tractable hypothesis testing of our assumptions in a laboratory environment using model organisms and droids.

ACKNOWLEDGMENTS

REFERENCES

Aoki, I., 1982: A simulation study on the schooling mechanism in fish. *Bull. Japan. Soc. Sci. Fish.Fisheries.* **48** (8), 1081-1088.

Boeddeker, N., Lindemann, J., Egelhaaf, M. and Zeil, J., 2005: Responses of blowfly motion-sensitive neurons to reconstructed optic flow along outdoor flight paths. *J. Comp. Physiol. A.* **191**, 1143-1155.

Borst, A., 2007: Correlation versus gradient type motion detectors: the pros and cons. *Philos. Trans. R. Soc. B.* **362**, 369-374.

Borst, A. and Egelhaaf, M., 1989: Principles of visual motion detection.. *Trends. Neurosci.* **12**, 297-306.

Casanova, P. and Deneubourg, J., 1999: L'intelligence collective, laboratoire de la mobilité. *Transports.* **397**, 354-360.

Collett, T., 2002: Insect vision: Controlling actions through optic flow. *Curr. Biol.* **12**, 615-617.

Couzin, I., James, R., Mawdsley, D., Croft, D. and Krause, J. 2006: Social Organization and Information Transfer in Schooling Fishes. *In: Brown, C., LaLand, K. & Krause, J. (Eds.)*, *Fish Cognition and Behavior.* Oxford, Blackwell Publishing Ltd, pp. 166-185.

Gaing, Z., 2003: Particle swarm optimization to solving the economic dispatch considering the generator constraints. *IEEE Trans. Power Syst.* **18** (3), 1187-1195.

Grégoire, G., Chaté, J. and Tu, Y., 2003 : Moving and staying together without a leader. *Physica D.* **181**, 157-170.

Halloy, J., Sempo, G., Caprari, G., Rivault, C., Asadpour, M., Tâche, F., Saïd, I., Durier, V., Canonge, S., Amé, Detrain, C., Correll, N., Martinoli, A., Mondada, F., Siegwart, R. and Deneubourg, J., 2007: Social integration of robots into groups of cockroaches to control self-organized choices. *Science.* **318**, 1155-1158.

Helbing, D., Farkas, I. and Vicsek, T., 2000: Simulating dynamical features of escape panic. *Nature.* **407**, 487-490.

Higgins, C., 2001: Sensory Architectures for Biologically Inspired Autonomous Robotics. *Biol. Bull.* **200**, 235-242.

Kirchner, H. and Thorpe, S., 2006: Ultra-rapid detection with saccadic eye movements: Visual processing speed revisited. *Vision Res.* **46**, 1762-1776.

Lythgoe, J., 1979: The Ecology of Vision. Clarendon Press and Oxford University Press, New York.

Ölveczky, B., Baccus, S. and Meister, M., 2003: Segregation of object and background motion in the retina. *Nature.* **423**, 401-408.

Pimentel, J., Aldana, M., Huepe, C. and Larralde, H., 2008: Intrinsic and extrinsic noise effects on the phase transition of swarming systems and related network models.. *Phys. Rev. E.* **77** (6), 061138-1 - 061138-17.

Rapoport, A., 1983: Mathematical models in the social and behavioral sciences. John Wiley & Sons.

Rind, F. and Simmons, P., 1999: Seeing what is coming: building collision sensitive neurons. *Trends. Neurosci.* **22**, 215-220.

Schlegel, T. and Schuster, S., 2008: Small circuits for large tasks: High-speed decision-making in archerfish. *Science.* **319**, 104-106.

Srinivasan, M. and Zhang, S., 2004: Visual motor computations in insects. *Annu. Rev. Neurosci.* **27**, 679-696.

Tsukamoto, Y., Smith, R. and Sterling, P., 1990: "Collective coding" of correlated cone signals in the retinal ganglion cell. *Proc. Natl. Acad. Sci. USA.* **87**, 1860-1864.

Vicsek, T., Czirok, A., Ben-Jacob, E., Cohen, I. and Shochet, O., 1995.Novel type of phase transition in a system of self-driven particles. *Phys. Rev. Lett..* **75** (6), 1226-1229.

Wagner, H., 1986: Flight performance and visual control of flight of the free-flying housefly (Musca domestica L.) III. Interactions between angular movement induced by wide- and small field stimuli. *Philos. Trans. R. Soc. B.* **312**, 581-595.

Warburton, K., 1997: Social forces in animal congregations: interactive, motivational, and sensory aspects. *In: Parrish, J. & Hamner, W. (Eds.)*, *Animal Groups in Three Dimensions.* Cambridge, Cambridge University Press, pp. 313-333.

SECURITY CLASSIFICATION & PUBLIC INFORMATION RELEASE FORM
26th Army Science Conference

The purpose of this form is to document the security, OPSEC, and public information reviews of papers submitted for the 26th Army Science Conference (26th ASC) and to authorize presentation, videotaping, audiotaping and publication to CD/web (www) of papers selected for presentation at the 26th ASC, JW Marriott Orlando Grande Lakes, Orlando, FL, 1-4 December 2008. This form must accompany the final summary and manuscript. Without its completion, the summary and manuscript will not be considered for presentation or publication. Please complete all blocks and affix signatures.

TITLE OF PAPER: Communication Properties of Self-Organizing Networks
(SWARMS) As Inferred From Optical Mechanics

NAME AND ORGANIZATION OF PRINCIPAL AUTHOR: B. Lemasson, University
of Washington, School of Aquatic and Fishery Sciences

TELEPHONE: (Commercial Only): 206-543-4772

PART I. SECURITY/OPSEC REVIEW - The final summary and manuscript must be reviewed by an authorized Security Officer IAW guidance under AR 380-5, DoD Directive 5200.20, AR 530-1, the Military Technologies List, and any other applicable security regulations. The paper must be unclassified and may not contain Restricted Data, Formerly Restricted Data or be marked NOFORN.

1. [✓] The summary is **UNCLASSIFIED/ PUBLIC DOMAIN.** (Only unclassified/ public domain summaries will be accepted.)

2. [✓] The final manuscript is **UNCLASSIFIED/ PUBLIC DOMAIN** and suitable for release and publication.

3. [✓] The manuscript and summary have undergone OPSEC review, and it has been determined that the material is suitable for release and publication in the public domain.

4. [ ] The proposed presentation has been reviewed to assure that classified information is not disclosed and that material is suitable for release to DoD attendees and cleared representatives of NATO/ ABCA countries.

5. Typed Name, Title, Grade, and Organization of OPSEC Reviewer   Signature of OPSEC Reviewer

TIM RAINES, ERDC OPSEC Officer, GG-11   _[signature]_   23/ May/ 2008

6. Typed Name, Title, Grade, and Organization of Security Reviewer   Signature of Security Reviewer

ERDC Command
LINDA D. MCGOWAN, Security Manager, GG-18   _[signature]_   23/ May/ 2008

PART II. INFORMATION RELEASE REVIEW. All papers must be reviewed for suitability of release (IAW AR 380-5), editorial accuracy, content and propriety. The reviewer must be knowledgeable of the research presented in the paper and cannot be an author or coauthor of said paper. No additional editing of this manuscript will be made prior to publication.

7. [✓] The summary and manuscript have been reviewed for conformance with release policy, editorial accuracy, content and propriety. They are suitable for presentation and publication in the public domain.

8. Typed Name, Title, Grade, and Organization of Information Release Reviewer   Signature of Information Release Reviewer

RICHARD E. PRICE, PhD, Chief, Environmental
Processes & Engrg Div, DB-5, ERDC   _[signature]_   5/25 2008

Please fax completed form to 757-357-5108.

CONSENT TO PUBLISH AND TRANSFER OF COPYRIGHT

Under United States Copyright law, the transfer of copyright from the contributing author(s) should be explicitly stated in writing to enable the publisher to publish and disseminate the author's work to the fullest extent. The following agreement must be signed by each contributing author and returned with your manuscript. The form will be sent to the publisher should your work be selected for publication.

TITLE OF PAPER/ARTICLE: Communication properties of self-organizing networks (swarms) as inferred from optical mechanics

AUTHOR(S): Bertrand Lemasson, James J. Anderson, and R. Andrew Goodwin

PART A – COPYRIGHT TRANSFER FORM AND WARRANTIES

NOTE: Part A applies only to authors who are not U.S. government employees or whose submitted work is not a result of their official U.S. government duties. If the paper/article was prepared as part of the writer's duties for his/her non-U.S. government employer (a "work for hire"), this agreement must be signed by the employer as an Author. If the paper/article was prepared by a U.S. government employee as part of his/her official duties, please refer to Part B.

1. The undersigned author or authors ("Author") of the above paper/article ("Article") transfers and assigns exclusively to the selected publisher ("Publisher") all Author's right, title and interest in the Article including, without limitation, the copyright therein. These rights include without limitation, translation rights, mechanical, electronic and visual reproduction; electronic storage and retrieval; and all other forms of electronic publication or any other types of publication including subsidiary rights.

2. In return for said rights, the Publisher grants to the Author the following rights:

    a. All proprietary rights relating to the Article, other than copyright, such as patent rights.

    b. The right to use, after publication, part or all of the Article in subsequent works of the Author, provided written permission is granted by the Publisher and the proper acknowledgment is made to the source and to the publisher.

    c. The right to make oral presentation of the material in any form.

    d. In the case of work performed under United States Government contract, Publisher grants the U.S. Government royalty-free permission to reproduce all or portions of the Article and to authorize others to do so for U.S. Government purposes.

3. Any other use or reproducing of the work may require a fee and/or permission from the Publisher.

4. In the event the Article is not published, this agreement becomes null and void.

5. The Author warrants and represents that the Article is original work and has not been published before in any form and that it does not infringe upon any copyright or other right(s), that it does not contain infringing or other unlawful matter, that he or she is the sole and exclusive owner of the rights here-in conveyed to the Publisher, and that he or she has obtained the customary permission from the copyright owner or their legal representative whenever information from copyrighted material is quoted or a table or illustration from such material is used. The Author will indemnify the Publisher for, and hold the Publisher harmless from any loss, expense or damage occasioned by any claim or suit by a third party for copyright infringement or arising out of any breach of the foregoing warranties as a result of publication of the Article. The Article shall be delivered to the Publisher free of copyright charges.

_____   _____
AUTHOR(S) (and TITLE, if not author(s))   DATE

PART B – U.S. GOVERNMENT EMPLOYEE CERTIFICATION

NOTE: If your work was performed under a U.S. Government contract, but you are not a government employee, sign Part A of this form (above) and see Item 2d. of Part A.

This will certify that ~~all~~ one authors of the above paper/article are employees of the U.S. Government and performed this work as part of their employment; that the paper/article is therefore not subject to U.S. copyright protection; and that no assignment of any copyright interest in the paper/article is made by this document. In the event that the paper/article is published in any foreign countries in which copyright protection is available under the laws of such countries, and Publisher acquires a copyright in the paper/article, Publisher grants to the U.S. Government a perpetual, paid-up, worldwide license to reproduce, copy, or otherwise use the paper/article in any manner.

PA Goode — Research Environmental Engineer   _9/10/08_

AUTHORIZED SIGNATURE/TITLE   DATE

US Army Engineer R + D Center

NAME OF GOVERNMENT ORGANIZATION